ORGANIC FLUVIAL SEDIMENT: PALYNOMORPHS AND "PALYNODEBRIS" IN THE LOWER TRINITY RIVER, TEXAS[1]

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ABSTRACT

In 1961–1962, the author studied the lower Trinity River, Texas, for palynomorph content, as a model of how pollen, spores, and palynodebris reach depositional areas for incorporation in sedimentary rocks. The river was selected partly because it was at that time relatively undisturbed by industry and damming. Three stations were selected for surface and mid-depth water sample collection, 00 in Trinity Bay, 04 on the Trinity River delta, and 09 on the lower Trinity River. Palynomorph loads at 04 and 09 were especially high, often reaching 10^5 or more per 100 liters of water. Water of the bay station usually contained much lower concentrations of palynomorphs. A wide range of pollen and spore types occurred in the water, dominated by major floral elements of the lower Trinity River area, but including forms from farther upstream. Reworked pollen and spores, eroded from rocks hundreds of kilometers north and northwest of the sampling localities, were regularly recovered. *Engelhardia/Momipites*-type pollen of Paleogene age was an especially significant reworked form. There were seasonal changes in the composition of the palynoflora, reflecting flowering peaks such as that of *Taxodium* (swamp cypress) in late winter and Poaceae (grass) in summer. In 1985–1986, the same stations were once again sampled. Since the earlier sampling, damming upstream had created Lake Livingston, which acts as a huge settling basin, resulting in decreased palynomorph load in the water at all stations in the lower river. Fungal spores as well as pollen apparently have been reduced in concentration. A sampling in 1986 of the lake itself and of the river at its inlet tends to confirm that the lake acts as a settling basin for waterborne palynomorphs. Rivers deliver a sampling of the terrestrial flora, via palynomorphs and palynodebris, to the continental shelf. In total, this particulate organic matter is an important part of the earth's budget of buried carbon. Studies of the palynomorph-palynodebris load of streams therefore contribute to understanding the origin and fate of organic matter in sedimentary rocks.

The carbon, or organic, cycle normally returns most organic matter to the hydrosphere and atmosphere as CO_2 and H_2O, with the release of energy. Cellulose and related compounds of the earth's biomass locked up in terrestrial plant tissues, especially wood, provide a relatively brief exception or delay to the cycle, but the interruption in the case of old trees can be much longer than it is for animals. Also, the total bulk of carbon tied up in living land plants is much greater than that stored in animals—most biomass is forest biomass. Furthermore, plant tissues incorporated in peat can remove carbon from the organic cycle for millions of years, in the form of peat, lignite, and higher-rank coal deposits. Coal deposits are a relatively rare geologic phenomenon, requiring an environment of deposition in which water depth remains in the tens-of-centimeters range for long periods, approximately 10^5–10^6 years for thick, commercially exploitable coal beds. Palynologists, as "dissolvers" of rock, have long been aware that sediment delivered by streams to the continental shelf, there producing the ubiquitous sandstones and shales of the geologic record, is almost always rich in

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plant tissues of all sorts. Bits of wood are the most common ingredient, but leaf fragments, especially cutinized epidermal pieces, bark residues, spores and pollen, as well as amorphous, more or less degraded plant material, are also common. It is this organic residue from sedimentary rock, especially of silty shale, that provides the subject matter of paleopalynology. Such plant debris, dispersed in the sedimentary rock, usually comprises a minor constituent by weight of the rock, less than 2% on average (Degens, 1965: 203). The organic matter content of sedimentary rocks varies from 0% for a very clean, nonorganic shale or sandstone, to 50% in a highly carbonaceous shale, to 97% in a few very pure coals. Palynologists usually refer to the pollen and spores either as "palynomorphs," a category that technically includes many other sorts of things representing all of the kingdoms of organisms except Monera, or as "sporomorphs," exclusively embryophyte pollen and spores. The rest of the microscopic plant organic matter, or detritus, dispersed in sedimentary rock is sometimes called "palynodebris."

Sporomorphs and palynodebris clearly have a lot to tell us about various environmental factors that operate during and after deposition of sediment. The spore and pollen floras indicate much about the environments pertaining on the land surfaces from which they were derived. The younger the sediments (and thus the more closely related the vegetation is to modern floras), the more accurately this information can be applied. For Pleistocene sediments it is possible now to reconstruct from the pollen record the source forest composition and dynamics with great precision (Bradshaw, in press; Jackson, in press; Traverse, 1988: 386–389). In older sediments we are not so certain of the autecological implications of each fossil plant taxon. Nevertheless much valuable information can be derived from ancient palynofloras about the environmental conditions on land where the producing plants grew, especially when the palynological information is coupled with data about megafossil plants (Phillips & DiMichele, 1981; Phillips et al., 1974, 1985; Scott, 1978, 1979). This is analogous to the fact that Pleistocene palynology depends on information from modern botanical studies.

Spore/pollen floras also reveal information about the *sedimentary* environment(s) by means of which they found their way to their final resting place. In 375 × 10^6-yr.-old Devonian shale-sandstone deposits of New York State and vicinity, Schuyler & Traverse (1990) have shown that spores are most abundant in river channel sediments, where they were quickly and "efficiently" covered, and least abundant in overbank (flood) deposits, where atmospheric oxygen had too good a chance to destroy the sporopollenin of the spore exines before they could be covered. The concentration of spores in these Devonian sediments was, however, about 10% of comparable Cenozoic sediments. Other studies back to the time of Hoffmeister (1954) and Muller (1959) have demonstrated that palynomorph concentration is related to proximity of ancient shorelines, water turbulence, and current directions (see Traverse, 1988, Chapter 17). Though the subject is in its infancy, investigations of nonspore palynodebris promise to yield even more information about the sedimentary environments responsible for its deposition. It is now reasonably clear that terrestrial plant biomass is a major source, probably *the* most important source of organic matter in sedimentary rocks (Deuser, 1988; Ittekot, 1988; Kump, 1988). At least part of this carbon bankroll may lead to hydrocarbon generation—petroleum and natural gas.

The magnitude of the accumulation of organic debris on the continental shelf is suggested by Chmura & Liu (1990), who report that one large river, the Mississippi, delivers about 1 × 10^{19} palynomorphs annually to the Gulf of Mexico. Assuming this is correct, it is easy to calculate by several techniques that about 4 × 10^4 metric tons of palynomorphs per year are deposited in this way on the Gulf shelf—a sizable annual increment of sporopollenin—but this is only a fraction of all plant debris so sedimented. For comparison it should be noted that all of the major rivers of the world are estimated to carry to the continental shelves about 150 × 10^6 metric tons of chemically resistant particulate organic matter (POC; Deuser, 1988; Ittekot, 1988). Mostly this is what palynologists call palynodebris. It is therefore obviously of interest to trace the movement of plant debris, most of which is microscopic in size, in streams, from the source vegetation to the site of deposition, usually on the continental shelf.

TRINITY RIVER, TEXAS

RATIONALE FOR SELECTION AND DESCRIPTION OF SITES

Trinity River (see Fig. 1) was selected for study in about 1960, because at that time there had been relatively little disturbance of the watercourse by dams, levees, and industry (Traverse, 1990). Originally, multiple stations and multiple depths of sampling for a program of repeated collections were planned. Preliminary studies quickly indicated that

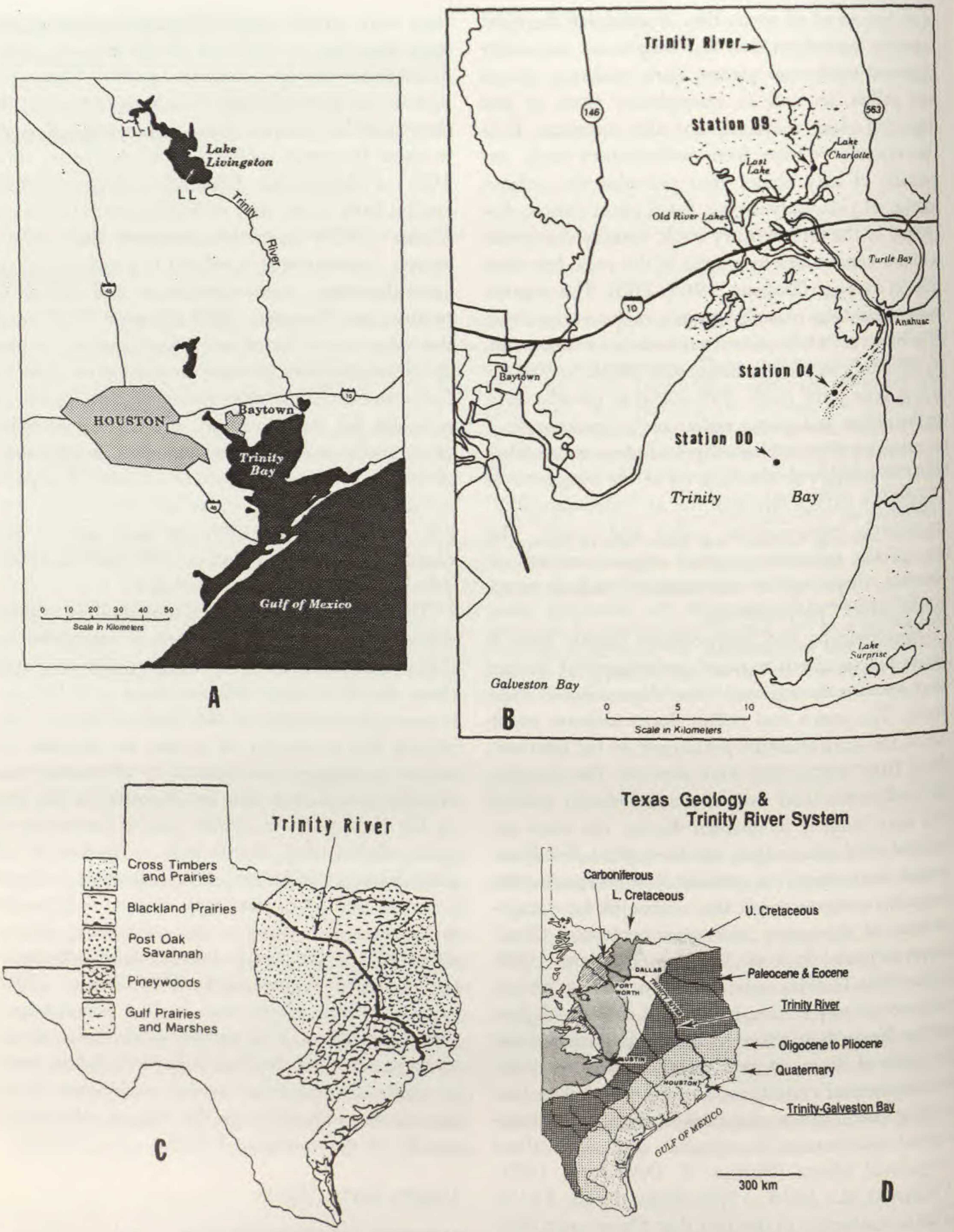


FIGURE 1. Geographic-botanical-geologic-setting for the lower Trinity River.—A. Lower Trinity River with Lake Livingston. Collection sites for Lake Livingston located by arrows. LL-I: inlet in middle of the river, where it discharges into the lake. LL: about 2 km north of the impounding dam. See B for details of collecting sites in the lower river and bay.—B. Lower Trinity River and Trinity Bay, showing sampling stations: 09, near Lake Charlotte, about 5 km north of highway I-10; 04 on the channeled deltaic extension; 00 in the center of Trinity Bay.—C. Vegetation areas through which the Trinity River passes. Station 09 is in piney woods near the Gulf prairies and marshes. Plant geographic information from Nixon & Willett (1974). For distances compare with D.—D. Course of the Trinity River from its source northwest of Ft. Worth to Trinity-Galveston Bay, showing the course of the river from older to younger rocks, Permo-Carboniferous to Pleistocene. (These illustrations first appeared in Traverse, 1990, and are reproduced here by permission of Elsevier Science Publishers.)

this was redundant, and sampling was limited to surface and mid-depth at three stations: 00 in the open bay, 04 on the outer Trinity River delta, and 09 on the lower river near Lake Charlotte. Each of these stations is still identifiable by prominent landmarks: an oil well head near station 00, navigational markers near 04, and an easily measurable distance north of a tributary at 09 (see Fig. 1). Therefore, the 1961–1962 collections could be compared to samples taken from the same stations in 1985–1986.

The area studied is a typical flat portion of the Gulf Coastal Prairie (see Fig. 1C, D). Extensive stands of pine (*Pinus*)–oak (*Quercus*)–sweet gum (*Liquidambar*)–hickory (*Carya*) forest typical for east Texas are present on the higher ground east and north of Turtle Bay and west of Old River Lake. The area immediately west of our station 09 consists of a *Spartina* grass prairie plus patches of standing water, with backswamps in which the dominant trees are *Taxodium distichum* (L.) Richard (cypress), *Salix nigra* Marshall (willow), and *Forestiera acuminata* (Michaux) Poiret (swamp privet). To the east of station 09, backswamps of this composition extend to Lake Charlotte.

Station 04 lies in the dredged Trinity River channel just off the lower part of the delta of the river, the vegetation on exposed parts of which is dominated by the giant grass ("reed"), *Phragmites communis* Trin., and other grasses (Poaceae), as well as sedges (Cyperaceae) and rushes (Juncaceae). The overwhelming bulk of this study area is covered by sedges and grasses. A gallery forest along the river as far south as Anahuac consists of *Salix nigra* Marshall, *Fraxinus pennsylvanica* Marshall (ash), *Taxodium distichum* (L.) Richard, *Carya aquatica* (Michaux f.) Nutt. (hickory), and other trees and shrubs. Backswamps near station 04 have vegetation like that of the galleries described above. Some shell banks support a flora atypical for the area, more reminiscent of limestone areas of central Texas, and characterized by *Diospyros texana* Scheele (Texas persimmon).

Beyond our study area, the Trinity River has its source northwest of Fort Worth and drains part of the Texas portion of the Great Plains, the Cross Timbers region (mostly forested with oaks), blackland prairies southeast of Dallas, extensive blackjack oak and post oak woodlands, and large areas of east Texas timber country, including the famed "Big Thicket." This east Texas forest is dominated by species of oak, pine, hickory, and sweet gum. Vegetation of this aspect extends south into our area, where it occurs as patches on deep sandy soils (Fig. 1C).

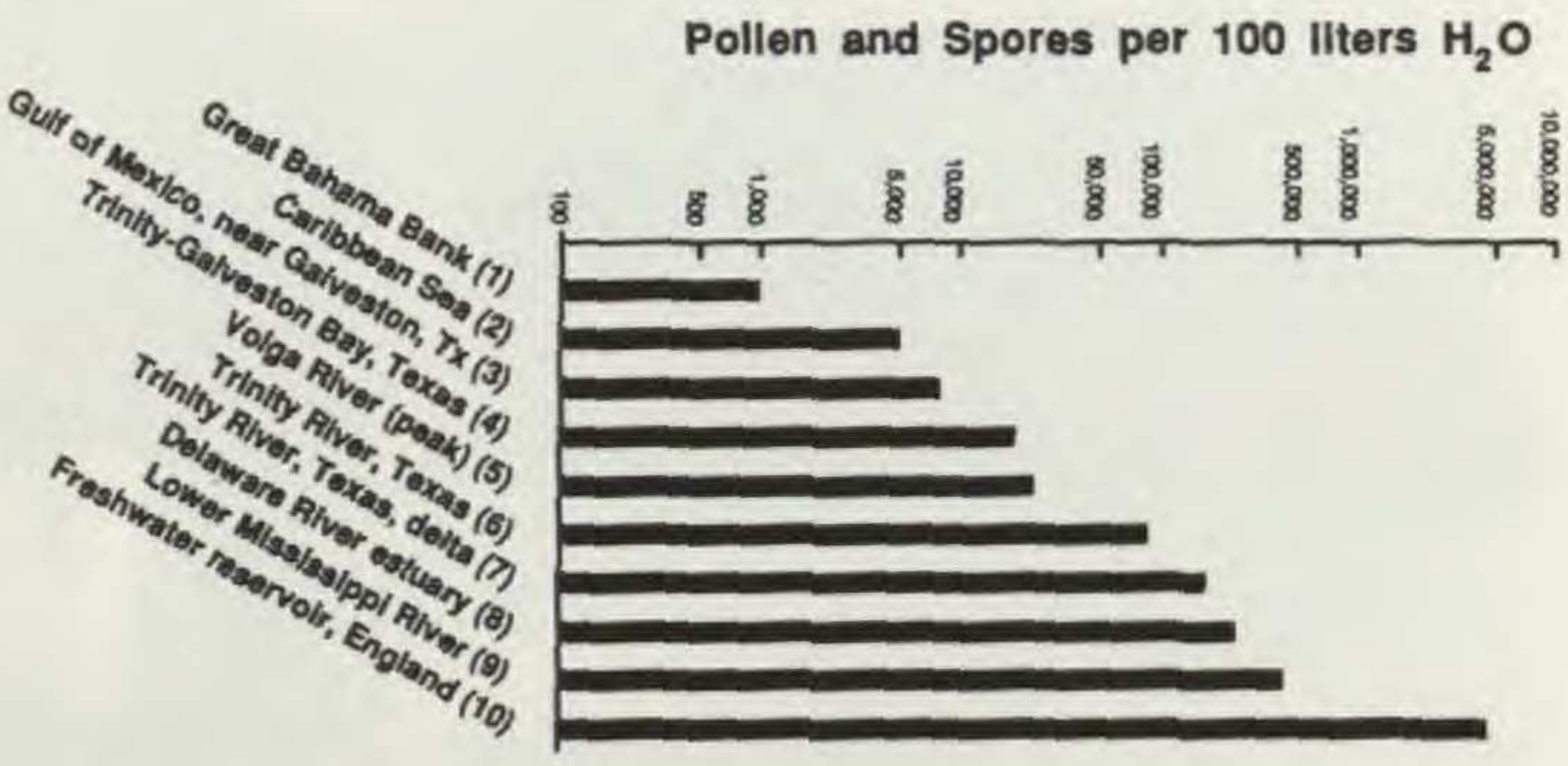


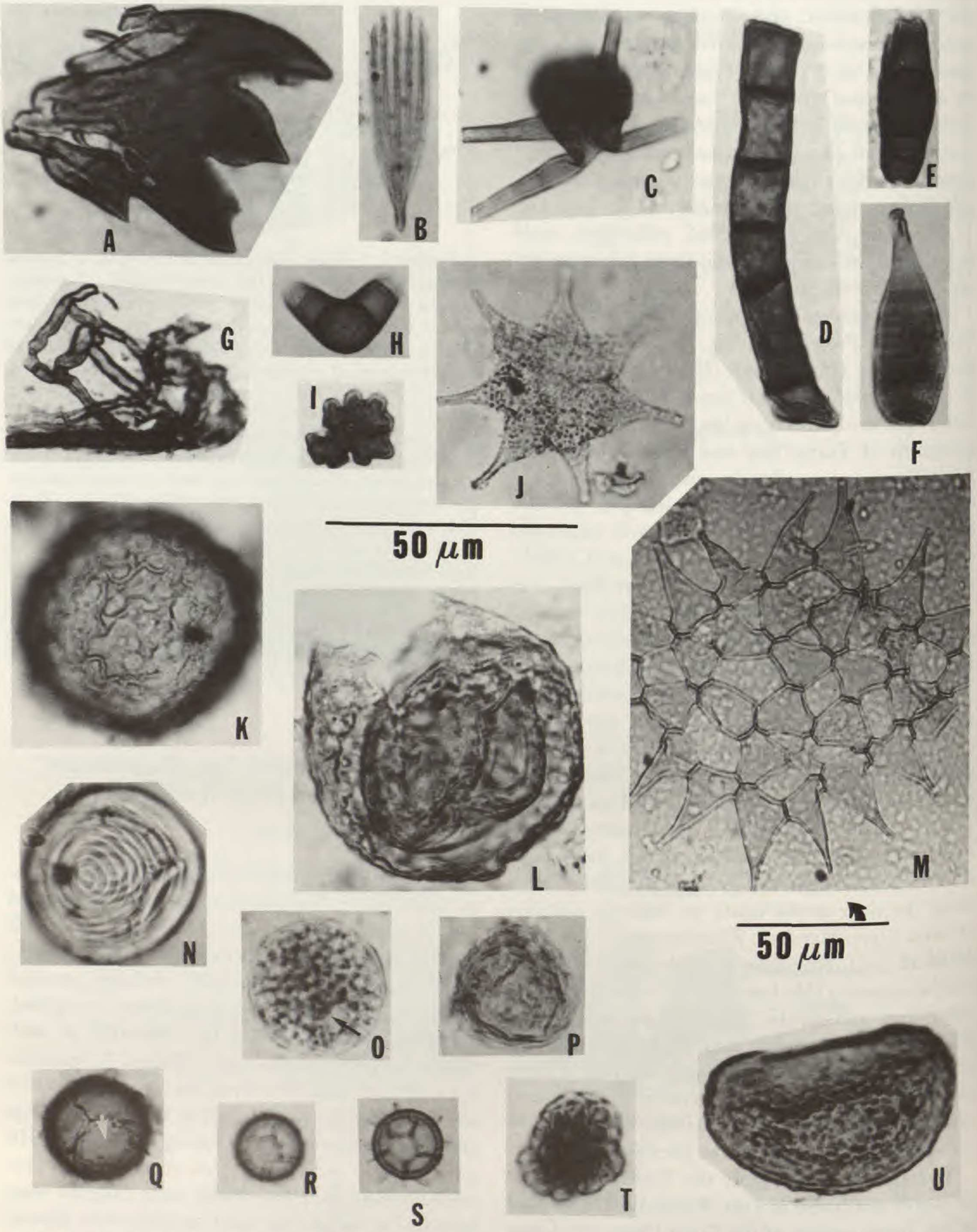
FIGURE 2. Pollen and spores in the water in various sedimentary situations. The concentration of palynomorphs per volume of water varies considerably from season to season and in response to storms and other factors. Therefore, all of the data with the exception of (5) are estimated averages for multiple measurements. Pollen and spores are expressed per 100 liters of water, as the numbers so generated are then similar to those for palynomorphs per gram of sediment. The data are plotted logarithmically. Water from mid-ocean localities would presumably contain at least an order of magnitude less per 100 liters than even the water of Great Bahama Bank. The reading of 5 × 10^6 per 100 liters of water for a small reservoir in England (10) is an indication of the high density that can be obtained in water with limited influx, closely surrounded by pollen-producing vegetation. Sources for data: (1) Traverse & Ginsburg (1966); (2) Farley (1987); (3, 4) Traverse (1990); (5) Fedorova (1952); (6, 7) Traverse (1990); (8) Groot (1966); (9) Chmura & Liu (1990); (10) Peck (1973).

STUDY OF PALYNOMORPHS AND "PALYNODEBRIS" PRESENT IN TRINITY RIVER WATER

MATERIALS AND METHODS

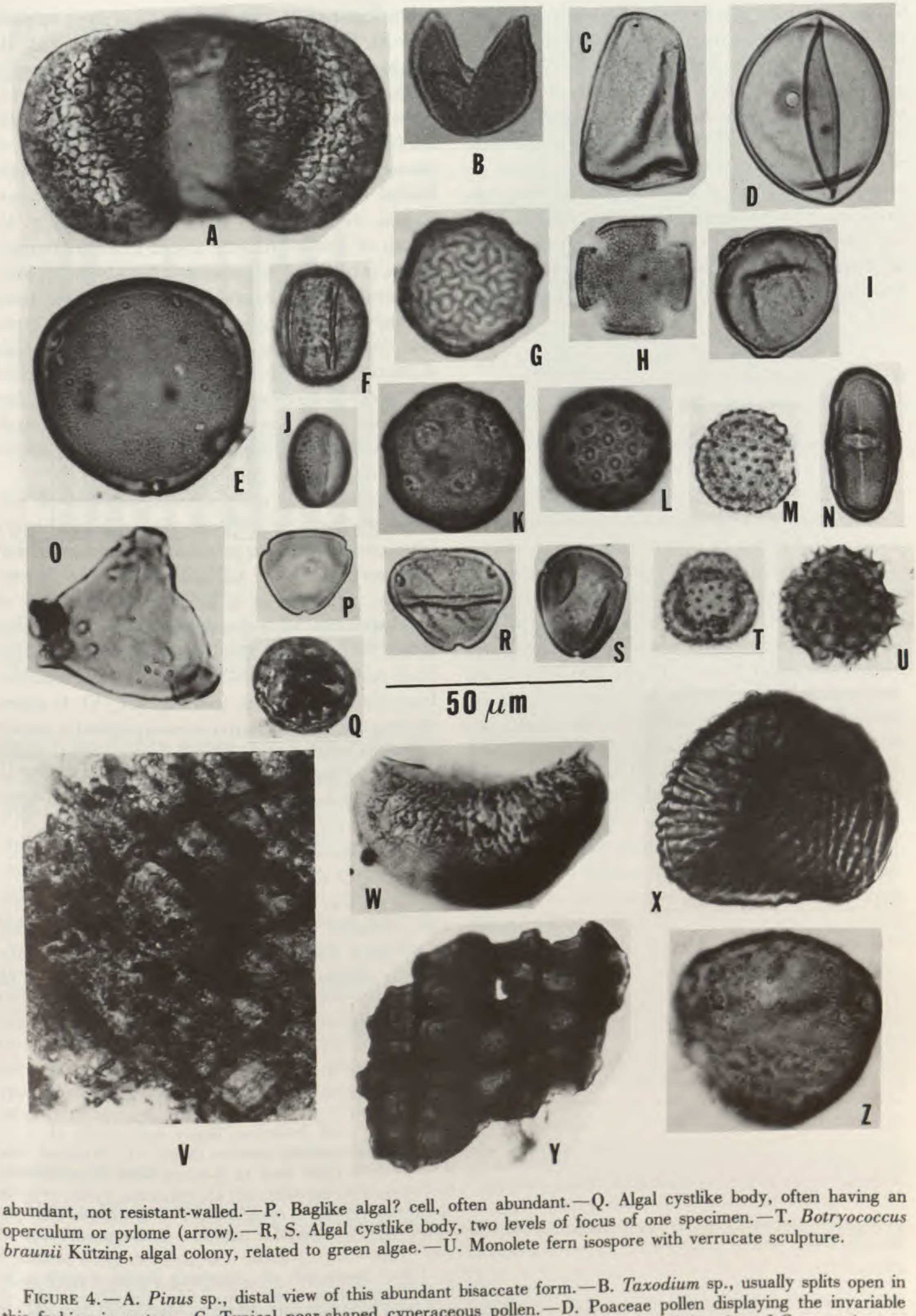
Approximately 20-liter (5-gallon) samples of water were taken. Mid-depth samples were obtained with gasoline-powered pumps. During 1961–1962 a specially designed outfit was used, but by 1985–1986 adequate commercially rentable gasoline pumps were available. In both instances a weighted, calibrated hose was used for collection at mid-depth. Surface samples were obtained by immersing a 20-liter tank directly in the water. The water was processed in 1961–1962 by boiling to a sludge and then processing the sludge by normal HCl-HF palynological procedures (see schedules in Traverse, 1988). In 1985–1986 some samples were boiled to a sludge, but most samples were filtered through silica filters, which were later dissolved in HF. Both techniques work well, but boiling is less trouble if the water contains much debris, because filters then clog quickly. The boiling technique requires careful monitoring, however.

The concentration of palynomorphs is expressed per 100 liters of water, because this yields numbers that are in the same range as palynomorphs per gram of sediment in rock samples. This convention



FIGURES 3 AND 4. Photomicrographs of the most important constituents of the palynoflora of the water of the lower Trinity River. Bars under 3I–J and 4R–S indicate the size of all of the specimens except for 3M, which has a separate bar.

FIGURE 3.—A. Chitinous, animal mouth part, perhaps of a polychaete worm.—B. Probably chitinous, though nearly colorless, lepidopteran wing scale. C–I. Brownish, chitinous fungal remains.—C. Possible germinating spore body.—D–F, H. Spore bodies.—G. Mycelia.—I. Sporeling.—J. Green algal coenobium, presumably *Pediastrum* sp.—K, L. Cyst or cystlike bodies, presumably algal, sometimes very abundant. The inner body seen in L is a frequent feature.—M. *Pediastrum* sp. coenobium.—N. Algal cystlike body. This form is commonly encountered in the Trinity River and in the water of other Texas streams investigated. Practically identical forms have been described as fossils, for example, as *Concentricystes* Rossignol.—O. Probable algal sphere, always with a condensed "eye" (arrow), often



abundant, not resistant-walled.—P. Baglike algal? cell, often abundant.—Q. Algal cystlike body, often having an operculum or pylome (arrow).—R, S. Algal cystlike body, two levels of focus of one specimen.—T. *Botryococcus braunii* Kützing, algal colony, related to green algae.—U. Monolete fern isospore with verrucate sculpture.

FIGURE 4.—A. *Pinus* sp., distal view of this abundant bisaccate form.—B. *Taxodium* sp., usually splits open in this fashion in water.—C. Typical pear-shaped cyperaceous pollen.—D. Poaceae pollen displaying the invariable annulate single pore and thin walls that collapse into folds during sedimentation.—E. Polar view of *Carya*, triporate hickory or pecan pollen (this example probably pecan).—F. *Quercus*, tricolporate pollen, equatorial view.—G. Polar view of *Ulmus*, multipored pollen with characteristic ridged sculpture.—H. Polar view of *Fraxinus* pollen with four

has been followed in previous publications on pollen in the water (Federova, 1952; Traverse & Ginsburg, 1966; Farley, 1987; Traverse, 1988). For pollen a ratio was also calculated to the "pollen sum," the total of wind-pollinated tree pollen. *Taxodium* was excluded from the pollen sum, because Shell Oil Co. palynologists, with whom I was associated at the time of the 1961–1962 research, excluded it for Cenozoic palynofloral studies, having noticed frequent, erratically occurring peaks of abundance of this pollen form in Neogene rock samples, which masked significant trends in other taxa.

MAJOR PALYNOFLORAL "PALYNODEBRIS" CONSTITUENTS

Pollen and spores are abundant in all streams and other bodies of water near-shore. Because sporopollenin is perhaps the most durable organic compound in existence, sporomorphs also are important in organic residues of sedimentary rock, ranging commonly from 1–2 × 10^3 per gram of sediment for Devonian shales to as high as 5 × 10^6 per gram for some Cenozoic coals (Traverse et al., 1961; Traverse, 1988). In water, pollen and spores range from about 1–5 × 10^3 per 100 liters in the open ocean (Farley, 1987; Traverse & Ginsburg, 1966) to 5 × 10^6 per 100 liters for some very small lakes in flood stage, when surrounding vegetation is flowering (see Fig. 2).

Figures 3 and 4 illustrate the major constituents of the waterborne palynoflora/palynodebris of the lower Trinity River. All kingdoms of organisms are represented except Monera: annelid worm mouth parts (3A), lepidopteran insect scales (3B), and abundant fungal spores and hyphae (3C–I), *Botryococcus* colonies (3T), and other algal material such as monads that would be classified by the palynologist as "acritarchs" (= "unknown origin") (3N–S), *Pediastrum* and related coenobia (3J, M) and some algal cystlike forms (3K, L); no certain fresh-water dinoflagellate cysts were encountered, however. Fern spores (3U) and gymnosperm pollen (4A, B) are abundant, and a great variety of monocot and dicot pollen, especially of wind-pollinated forms such as Poaceae, *Quercus*, *Ulmus*, *Carya*, *Ambrosia* and *Iva* (ragweed) (see Fig. 4). Pollen of animal- (mostly insect-)pollinated angiosperm taxa is also represented, but always in comparatively low numbers. The Trinity River flows through a considerable variety of vegetation types from its source in north-central Texas to the Gulf of Mexico (Fig. 1C). However, the dominant pollen and spore forms represent genera of plants that are found in the piney-woods and Gulf-prairie-and-marsh vegetational areas of the lower Trinity course relatively near the collection stations.

Palynodebris is a term not favored by all palynologists, because cellulosic plant tissues of many sorts are included, not just those with sporopollenin walls such as "true" palynomorphs have. Nevertheless, palynodebris is descriptive for pieces of wood and other tissue particles that are sedimented along with silt and sand-sized mineral particles. Such particles are abundant in all organic residues from the Trinity River (see Fig. 4V, Y). It seems obvious that if such matter is incorporated in anoxic sediment, or is covered by sediment quickly enough to prevent oxidation, considerable carbon-sinks on the continental shelves can be derived from palynomorphs and palynodebris.

Also noteworthy is the small but significant occurrence of obviously recycled forms (Fig. 4O–S, X), such as the Pennsylvanian spore *Triquitrites* sp., probably Cretaceous *Cicatricosisporites*, and Paleogene *Engelhardia* (*Momipites*). These are clearly derived from weathering and erosion of

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colpi and reticulate exine pattern. Also occurs commonly as tricolpate.—I. Polar view of 3-pored *Myrica* pollen.—J. *Salix*, equatorial view of tricolporate, reticulate pollen.—K. *Liquidambar*, multipored pollen with reticulate sculpture.—L. Multipored pollen of sort that many genera of Chenopodiaceae/Amaranthaceae produce.—M. Polar view of tricolporate, echinate (spiny) pollen produced by ragweed (*Iva* and *Ambrosia*, family Asteraceae), cf. T.—N. Equatorial view of tricolporate Umbelliferae (carrot) pollen with characteristic shoebox shape.—O. Proximal view of *Triquitrites* sp., a spore reworked from Pennsylvanian rocks.—P. Polar view of 3-pored fossil *Engelhardia/Momipites*-type pollen, reworked from Paleogene rocks.—Q. Chenopodiaceae pollen (cf. L), with many pyritic crystals inside.—R. 3-pored fossil juglandaceous pollen (*Engelhardia/Momipites*-type?) reworked as P.—S. Another example of 3-pored fossil juglandaceous pollen (*Engelhardia/Momipites*-type?); compare P and R.—T. Ragweed pollen as M.—U. Polar view of long-spined, insect-pollinated Asteraceae pollen.—V. "Clumpy" amorphous, partly degraded plant tissue infested with fungal mycelia.—W. Separated *Pinus* saccus (cf. A) containing pyrite crystals.—X. Characteristically ridged *Cicatricosisporites* spore, probably reworked from Cretaceous rock—the darker color of these spores distinguishes them from spores of extant ferns found in my samples; however, the illustrated form is very similar morphologically to spores of *Anemia mexicana* Kl., a fern still found in the Edwards Plateau of Texas, cf. Dettmann & Clifford (1991).—Y. Fragment of wood.—Z. *Carya* (cf. E) pollen showing extensive biological degradation (bacterial and/or fungal).

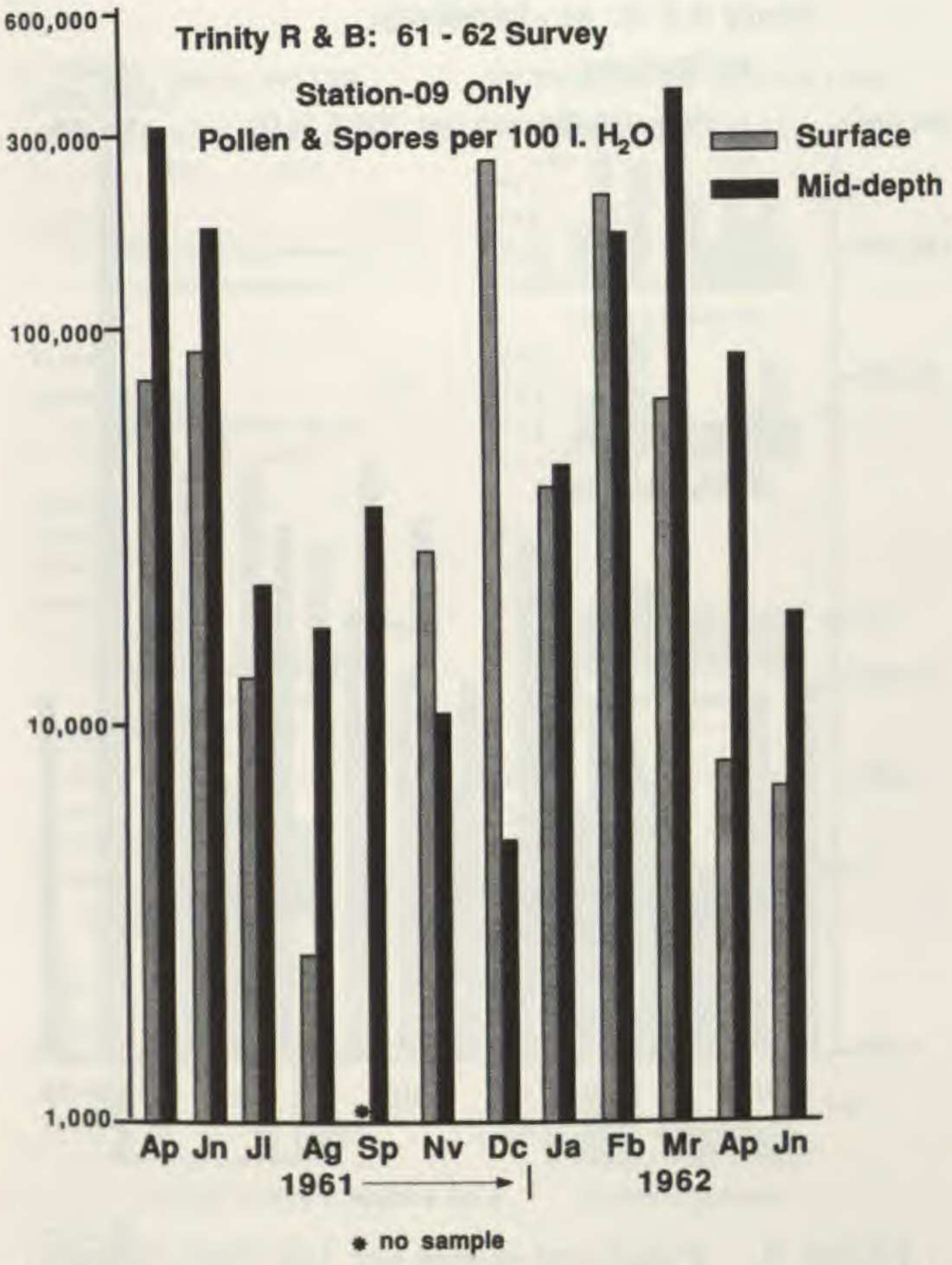

FIGURE 5. Amounts of pollen and spores per 100 liters of water at station 09 (see Fig. 1B for location), 1961–1962. Plotted logarithmically.

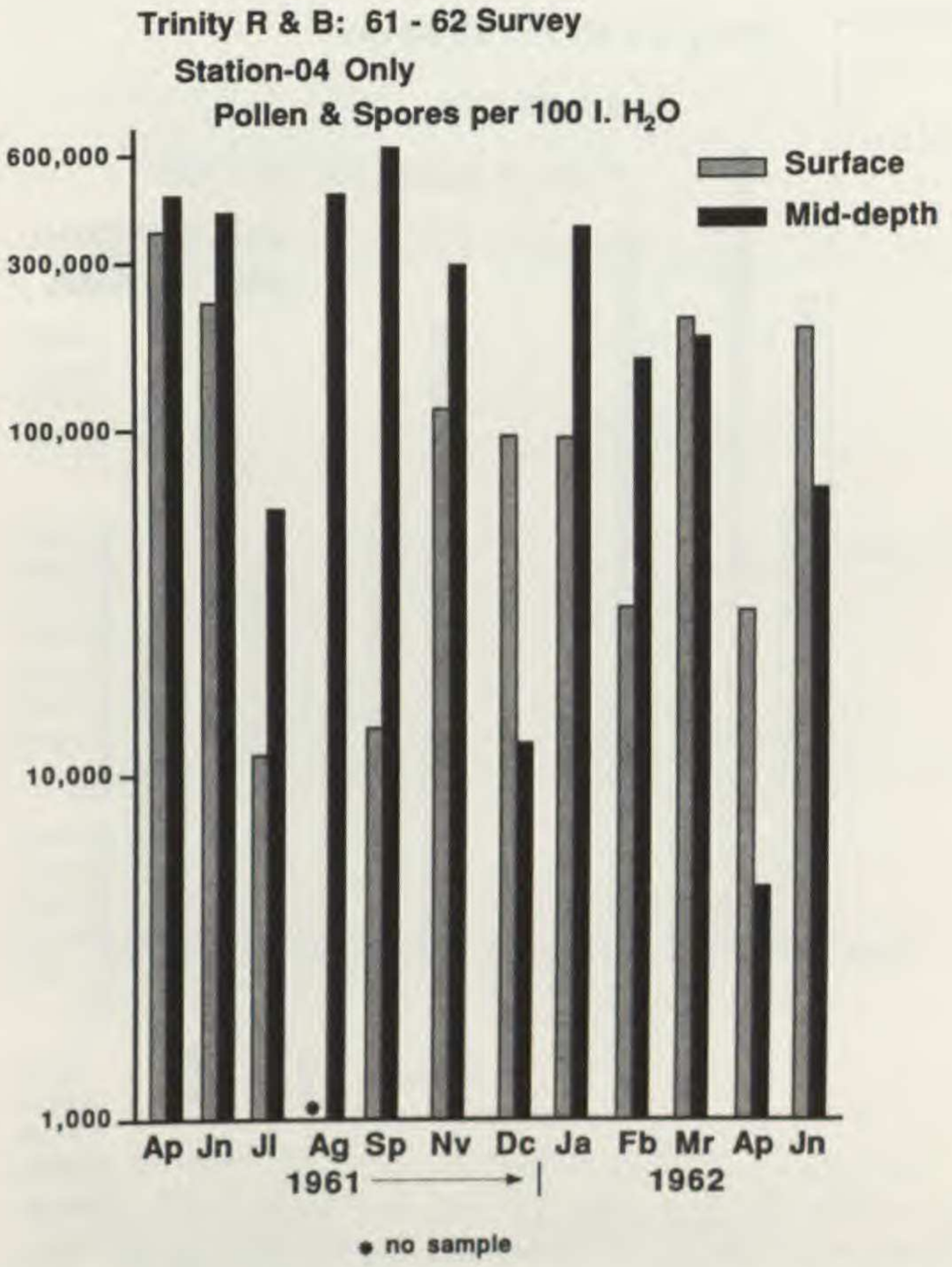

FIGURE 6. Pollen and spores per 100 liters of water at station 04 (see Fig. 1B for location), 1961–1962. Plotted logarithmically.

rocks in the Trinity course, which means that the *Triquitrites* has traveled some 750 km, *Cicatricosisporites* perhaps 500 km, and *Engelhardia* 200–300 km. Burgess (1987) has shown that in the Mississippi River, coal beds are eroded far upstream, probably more than 1,500 km, and particles of the coal-containing Pennsylvanian spores reach the Gulf of Mexico in fair abundance as "coffee grounds." Pyrite-filled grains, or parts of grains (Fig. 4Q), show that bacterial action under reducing conditions has occurred. Partially corroded spores and pollen (Fig. 4Z) demonstrate attack by microorganisms or by oxidation. Such fossils indicate that palynomorphs are affected by a variety of local environmental conditions during their eventful travels down the Trinity.

SEASONAL CHANGES

Station 09 in 1961–1962. Figure 5 illustrates the seasonal changes observed in 1961–1962 at station 09 in the river proper (Fig. 1). Note that pollen load frequently reached over 1×10^5 per 100 liters of water and was above 3×10^5 per 100 liters in April 1961 and March 1962. With few exceptions (November–December 1961, February 1962) the mid-depth water contained more pollen than surface water, meaning that for most of the year transportation consists predominantly of palynomorphs coming to the stream a day or many days before sampling. Surface samples include pollen newly arrived by air, and by runoff water, from the surrounding vegetation, as well as palynomorphs stirred up from below when flow is turbulent. In the late fall and winter months (January 1962 was only a slight exception), pollen in the superficial runoff water predominated over pollen in the mid-depth load of the river.

Station 04 in 1961–1962. Figure 6 shows the 1962–1962 seasonal changes at station 04, on the delta front (Fig. 1B). Observe first that the numbers are in general the largest for any of the three stations, reflecting continued discharge from the river into the delta channel, as well as pollen rain from abundant neighboring anemophilous vegetation. Mid-depth water contained more pollen than surface water except in December 1961 and March–June 1962. There is considerable tidal influence at station 04, and the relatively low mid-depth water pollen concentrations for some months may be accounted for by incoming, deeper, tidally influenced water, depleted of pollen. Also, because of tidal influence, fresh river water tends to "ride" out over the brackish, deeper water before mixing with it.

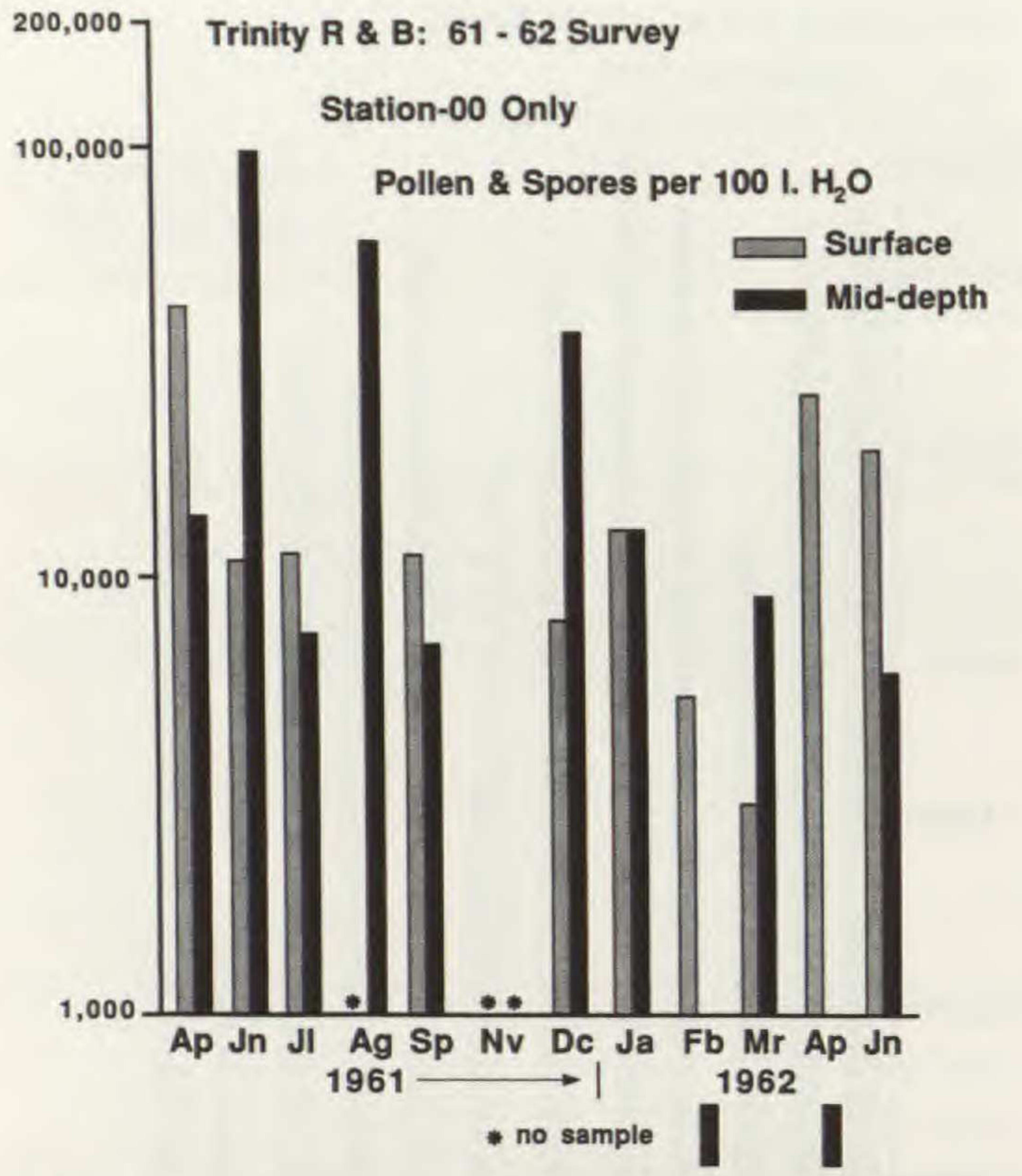

FIGURE 7. Pollen and spores per 100 liters of water at station 00 (see Fig. 1B for location), 1961–1962. Plotted logarithmically. The mid-depth readings for February and April 1962 are extremely low (less than 1,000), and they therefore plot below the 1,000 line.

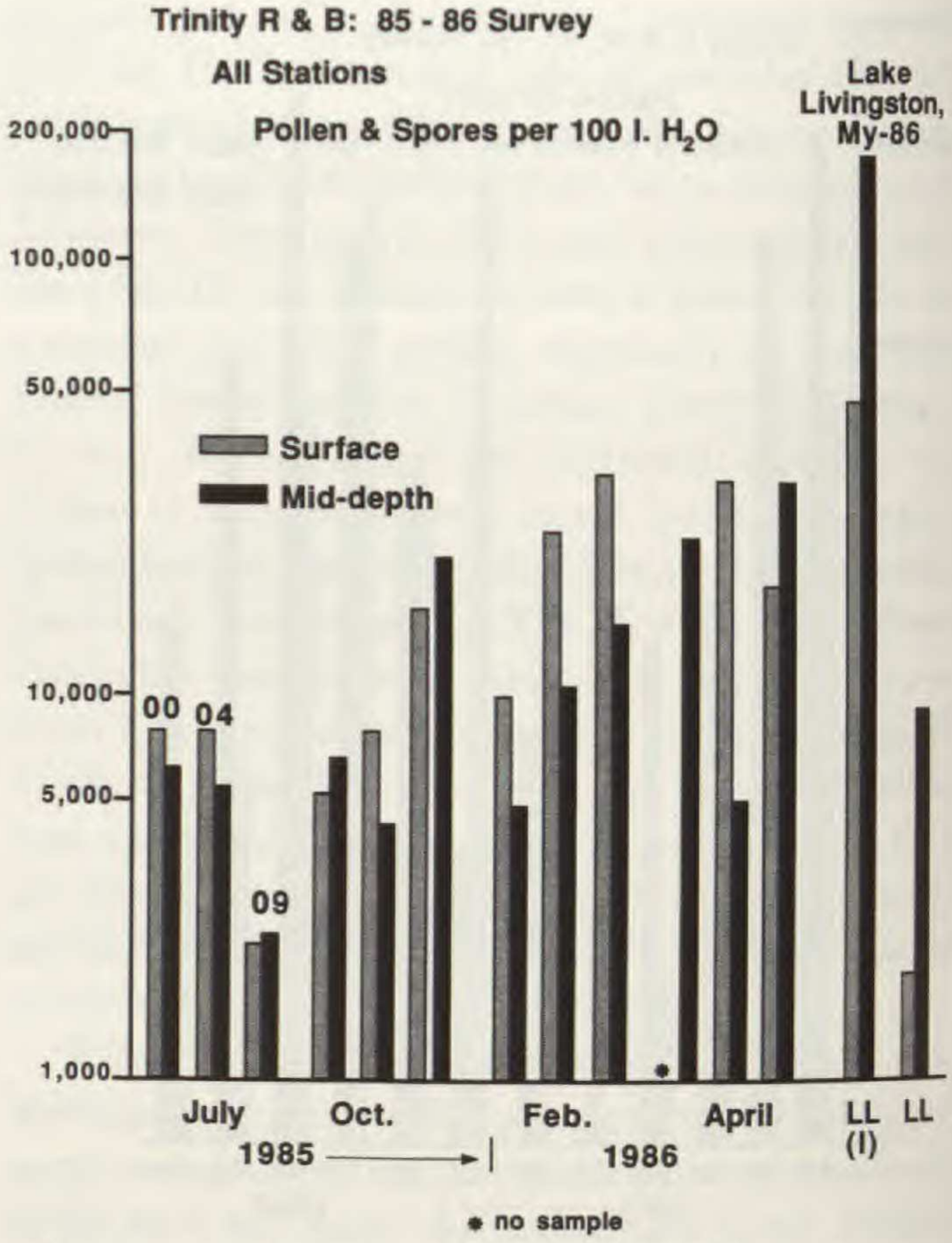

FIGURE 8. Pollen and spores per 100 liters of water, stations 09, 04, 00, and Lake Livingston, 1985–1986. The sequence of stations is the same for October 1985 and February–April 1986, as displayed for July 1985. See Figure 1A for Lake Livingston collecting sites. Plotted logarithmically.

Station 00 in 1961–1962. Figure 7 shows pollen concentration at station 00 in the open Trinity Bay (Fig. 1B). These are the lowest values for any of the stations, no sample exceeding 1×10^5 per 100 liters. Most were far less, as the water here is depleted of pollen by settling out (sedimentation). In contrast to other stations, most surface samples exceeded mid-depth samples in concentration. Two of the mid-depth samples (February and April 1962) contained the fewest palynomorphs of any of the 1961–1962 samples. Here, in the open bay, tidal movements probably greatly influence the relative pollen content, especially of mid-depth water.

Observations on pollen load of water at all stations in 1985–1986. In 1968, the U.S. Army Corps of Engineers completed a dam impounding a huge, artificial lake called Lake Livingston (see Fig. 1A). In 1985–1986, I made a few return visits to stations 00, 04, and 09, in order to sample the river under the presumably altered conditions. The results are displayed in Figure 8. Obviously, the pollen load of the lower river, now merely an outlet for Lake Livingston, is significantly depleted, by comparison with the pre-dam river. The conclusion, though based on only one year of measurements, seems obvious. The distributions of surface versus mid-depth concentrations do not seem greatly different from those observed in 1961–1962. However, the total reduction in palynomorph load by interpolation of Lake Livingston as a gigantic settling basin for sediment of all kinds, including pollen and spores, presumably tells the story. Note in Figure 8 that Lake Livingston water at the *inlet* is comparable to 1961–1962 values for the river proper (station 09). Water from well out in Lake Livingston taken the same day displays pollen load comparable to the present-day lower Trinity River, or to water taken from central parts of large lakes generally.

COMMENTS ON SPECIFIC TAXA

In 1961–1962, seasonal variation, and differences depending on position of the stations, were studied for some of the important sorts of pollen. The limited number of samplings in 1985–1986 seem to follow the same pattern, despite the considerable curtailment of total pollen load in 1985–1986, as compared to 1961–1962.

PROMINENT TREE POLLEN

A. *Quercus* (Figs. 9, 4F). Oak pollen is a major component at all stations and in all seasons. Oaks

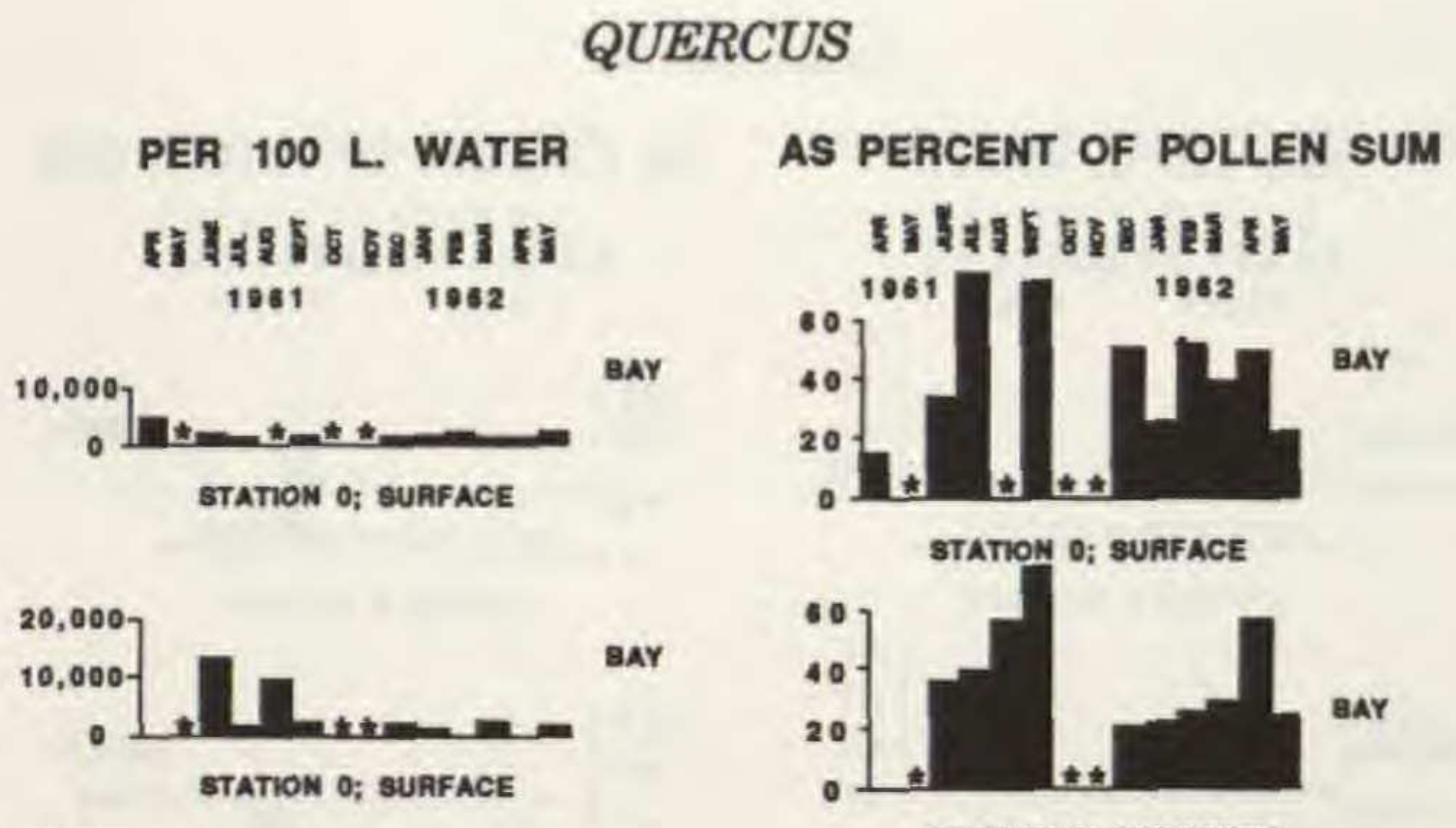

FIGURE 9. Monthly distribution of *Quercus* pollen, 1961–1962, at stations 09, 04, 00, expressed per volume of water and as percentage of pollen sum. Asterisk indicates no sample.

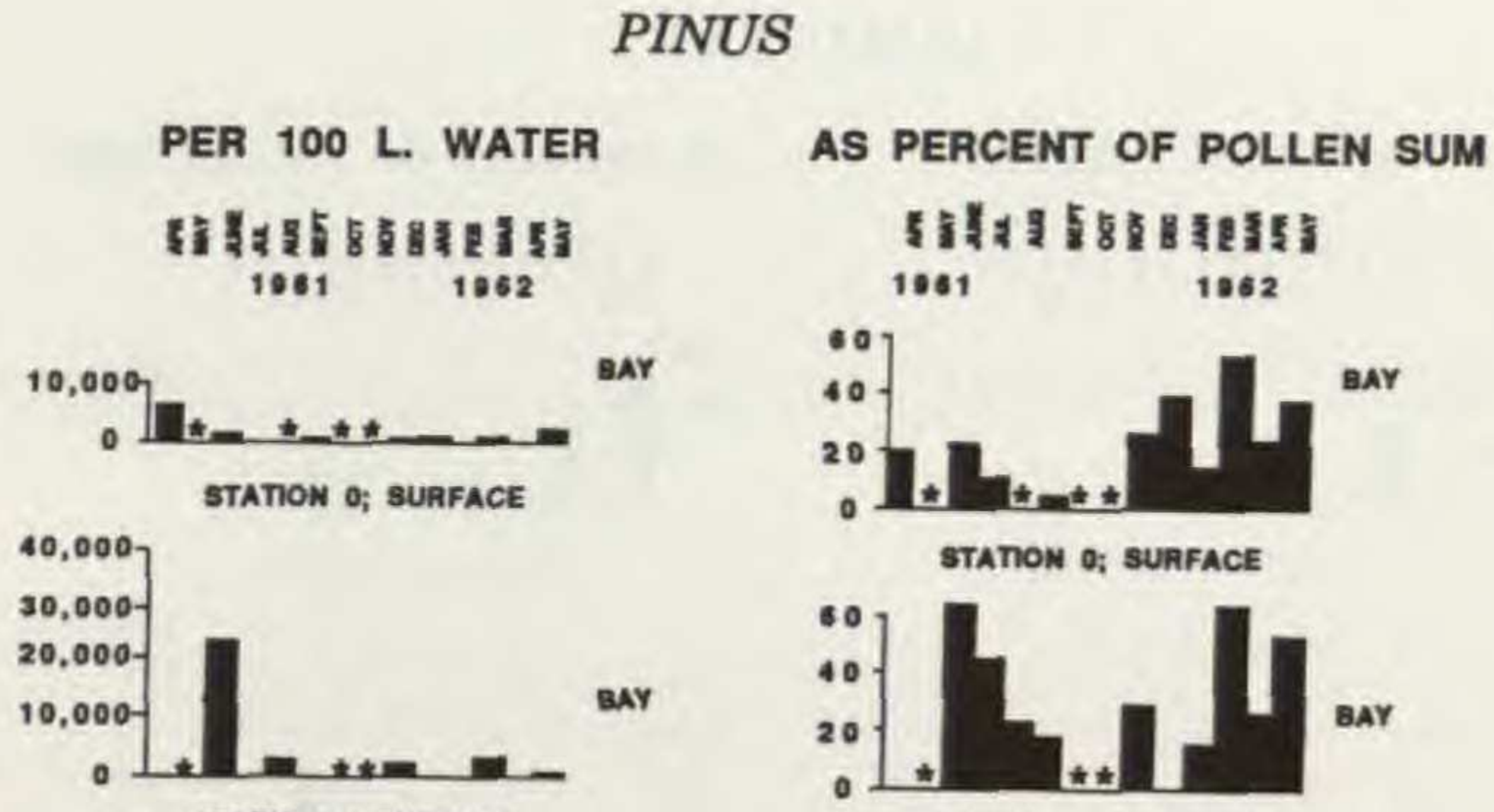

FIGURE 10. Monthly ditsribution of *Pinus* pollen, 1961–1962, at stations 09, 04, 00, expressed per volume of water and as percentage of pollen sum. Asterisk indicates no sample.

of many species are common throughout the Trinity drainage. Their pollen almost never drops below 20% of total palynoflora and is usually higher. On the basis of pollen per 100 liters of water, however, marked differences are observable. Relatively small amounts of *Quercus* pollen remain in the water of the bay. At the river station (09) and at the surface on the delta, the summer and fall concentration of *Quercus* pollen is low, whereas during the spring flowering period, amounts are high. Mid-depth water on the delta has anomalously high values during some summer months, presumably because of pollen being stirred up with other sediment from the bottom.

B. *Pinus* (Figs. 10, 4A). The distribution of pine pollen, both as to percentage, and as an amount of pollen per 100 liters of water, is very similar to that just described for oak pollen. The two are codominants of the pollen flora. *Pinus* species are also abundant in the drainage area. The low values per 100 liters of water in the bay confirm the overwhelming importance of hydrodynamic effects on pollen distribution in the lower Trinity River, as wind-blown pine pollen should reach the open bay just about as easily as it does the lower delta at station 04.

C. Ulmaceae (Figs. 11, 4G). This category includes several species of *Ulmus* and of the closely related *Planera aquatica* (Walt.) J. Gmelin (water elm). (*Celtis* pollen, although ulmaceous, is different morphologically and in distribution of the trees; it was counted separately.) The late fall and winter flowering periods of different species of elm are reflected in percentages and amount per 100 liters of water. Mid-depth values for the delta station (04) show the same stirring-up phenomenon described for *Quercus* and *Pinus* above.

D. *Taxodium* (Figs. 12, 4B). Swamp cypress pollen provides a clear-cut reflection of flowering time of the producing trees. Cypress produces pollen in January and February in the area studied. Significant amounts of *Taxodium* pollen at other times in mid-depth delta water must represent some combination of: (1) pollen stirred up with other

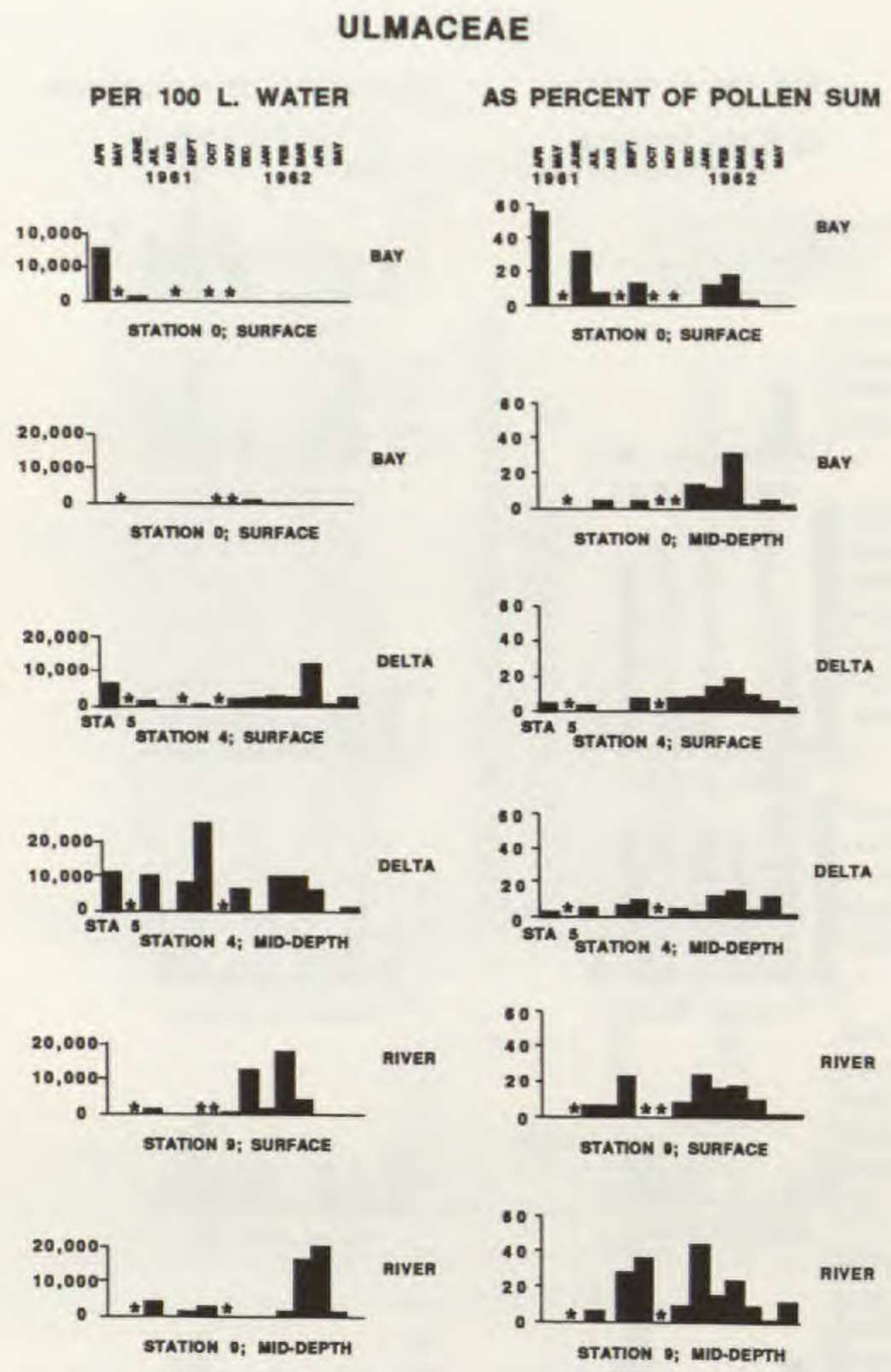

FIGURE 11. Monthly distribution of Ulmaceae pollen, 1961–1962, at stations 09, 04, 00, expressed per volume of water and as percentage of pollen sum. Asterisk indicates no sample.

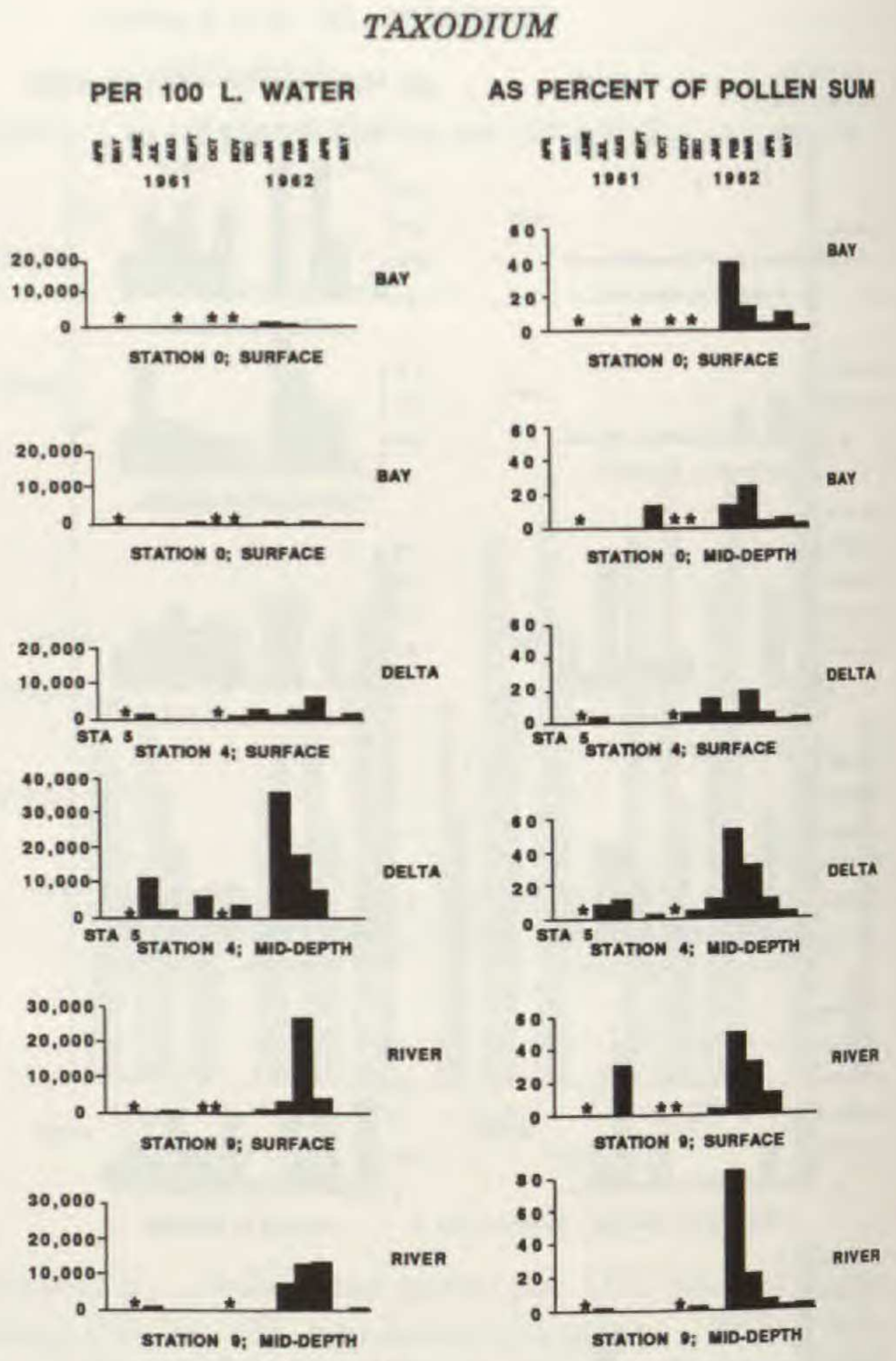

FIGURE 12. Monthly distribution of *Taxodium* pollen, 1961–1962, at stations 09, 04, 00, expressed per volume of water and as percentage of pollen sum. Asterisk indicates no sample.

sediment in the delta by river and tidal action, as in A–C above, or (2) pollen washed off of surfaces upstream.

E. *Carya* (Figs. 13, 4E). This genus includes all the hickory species of the area, as well as pecan. The record bespeaks the April–May flowering of the genus in this area, plus what I interpret as an influx of reworked *Carya* pollen in summer and fall that fits in quite well with records for *Engelhardia/Momipites*-type, a known reworked Paleogene form (see below). *Carya* pollen is known to be robust and frequently reworked.

F. *Engelhardia/Momipites*-type (Figs. 14, 4P, R?, S). This pollen type was produced by trees related to *Juglans* (walnut) and *Carya*. *Engelhardia* itself is, however, now extinct in the United States. (The genus, or closely related juglandaceous trees making pollen of the *Engelhardia/Momipites*-type, still exists in Asia, Mexico, and Central America.) Therefore, this pollen is obviously reworked from older, probably Paleocene–Oligocene deposits. Plotted with the pollen distribution is the approximate monthly total rainfall at Riverside, Texas, on the Trinity River, near the boundary between Oligocene and Eocene rocks. Occurrences of *Engelhardia/Momipites*-type are perhaps related to preceding heavy rains in these areas upstream. It is worth noting that there is no certain way to distinguish reworked pollen of *Quercus*, *Pinus*, and other extant genera from their recently produced counterparts (cf. especially *Carya*, above). The regular occurrence of reworked forms in surface water samples proves that the whole palynomorph load of the river is thoroughly mixed by turbulence when the rate of flow is sufficiently high.

PROMINENT HERBACEOUS FORMS

A. Poaceae (Figs. 15, 4D). Grass pollen is very difficult to separate as to genus, and this is not ordinarily attempted in palynological analysis. Grass pollen in Trinity River water shows strong seasonality, reflecting its summer–fall flowering. This is especially obvious in percentage-of-pollen sum calculations. The record for Cyperaceae (Fig. 4C) is very similar to that for grass, and both data sets show rather small concentrations of pollen in the water at station 09, presumably a reflection of the prevailingly wooded area in that vicinity and north of it.

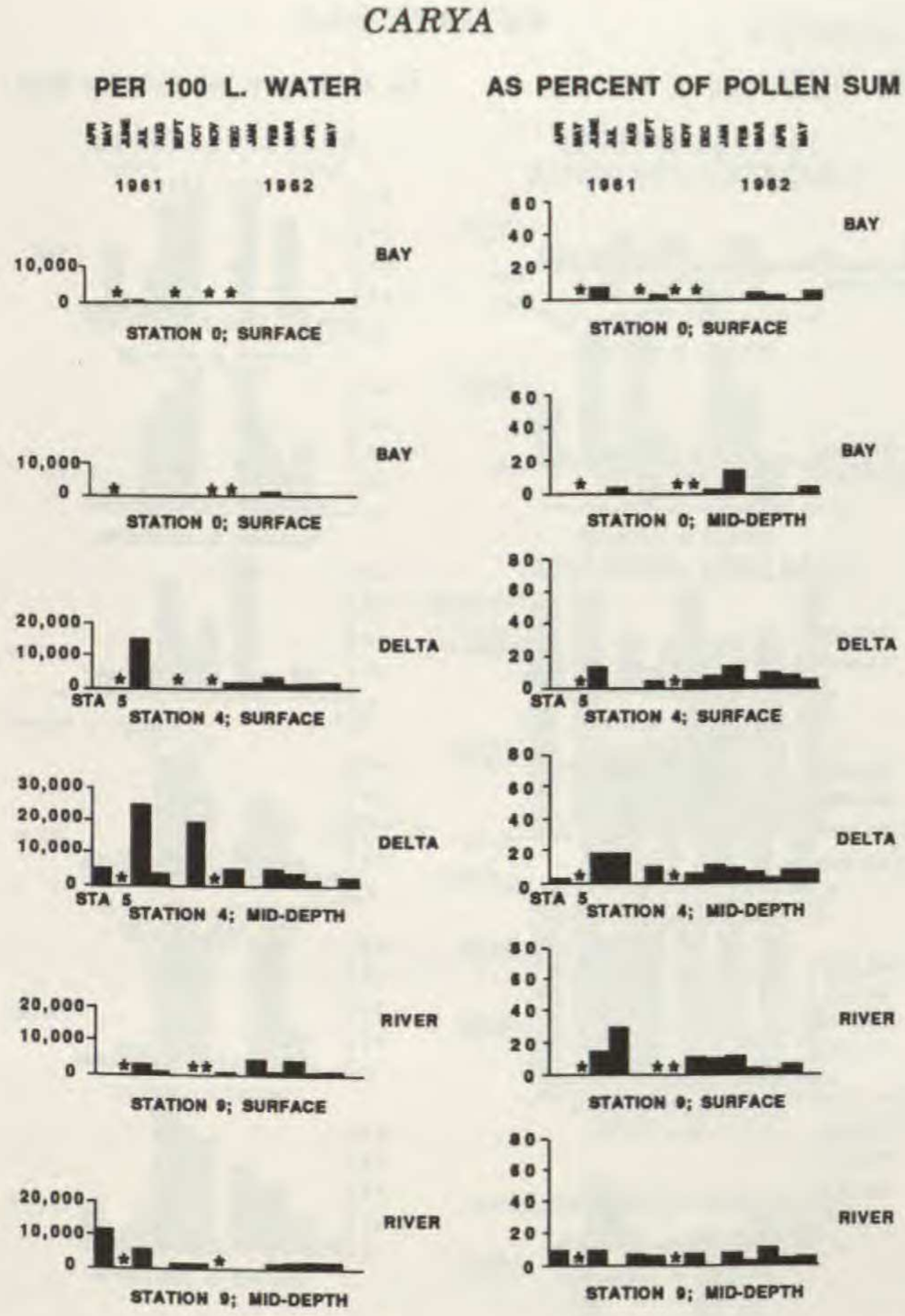

FIGURE 13. Monthly distribution of *Carya* pollen, 1961–1962, at stations 09, 04, 00, expressed per volume of water and as percentage of pollen sum. Asterisk indicates no sample.

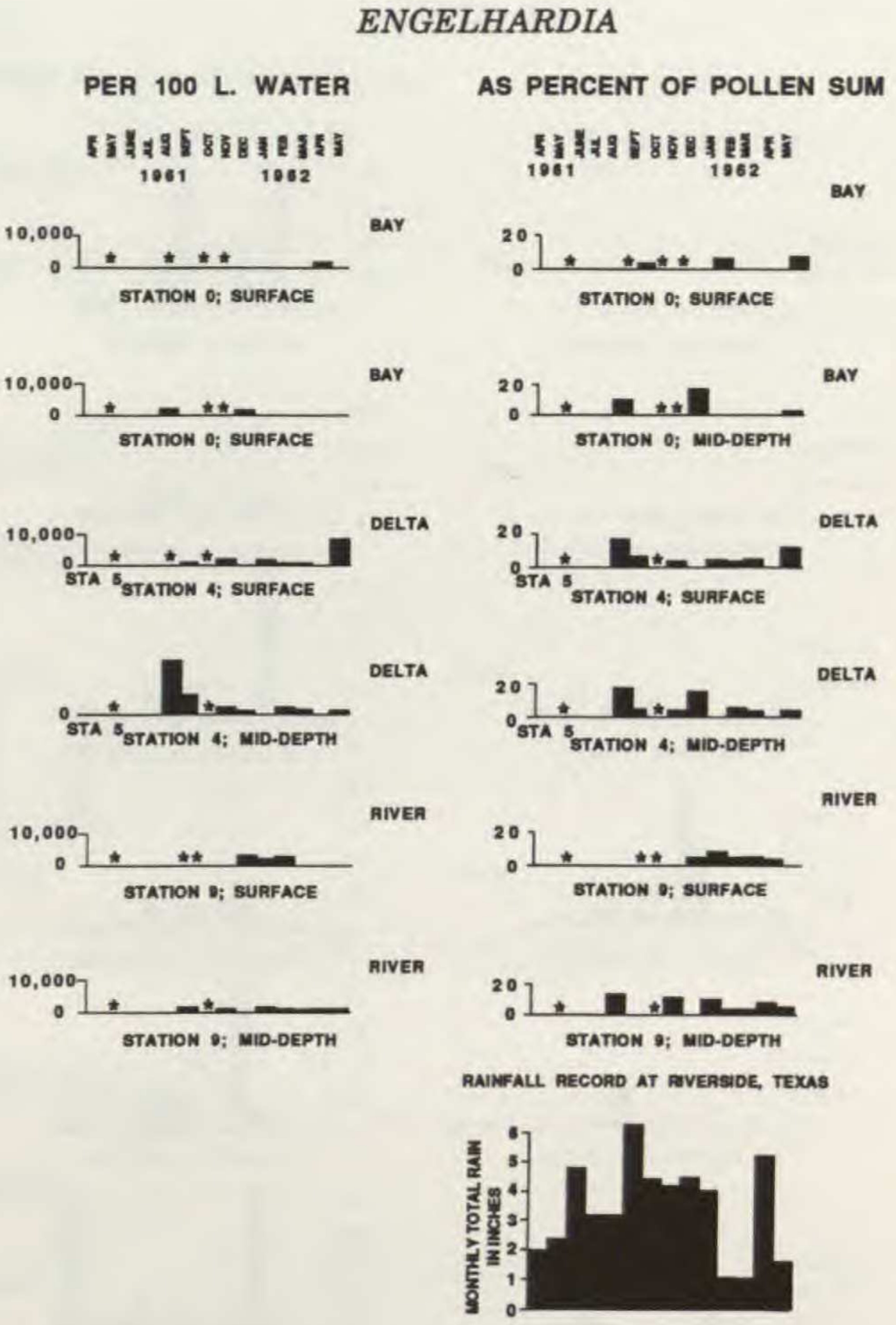

FIGURE 14. Monthly distribution of the reworked pollen of *Engelhardia/Momipites*-type, 1961–1962, at stations 09, 04, 00, expressed per volume of water and as percentage of pollen sum. The monthly rainfall record for Riverside, Walker County, Texas, upstream on the Trinity River, is plotted below. The reworked pollen record probably reflects erosion upstream. Asterisk indicates no sample.

B. Asteraceae (Figs. 16, 4M, T, U). This large family includes thistles (*Cirsium horridulum* Michaux), groundsel bushes (*Baccharis halimifolia* L.) and many others occurring in the subject area, both wind-pollinated forms such as ragweed (*Iva* spp. and *Ambrosia* spp.), which produce huge quantities of pollen, and insect-pollinated forms such as sunflower (*Helianthus* spp.), which produce relatively little. The common wind-pollinated composites flower in the summer and fall. This flowering pattern is reflected better as a percentage of pollen sum than in concentration per volume of water, which is influenced by other factors such as water velocity and turbulence.

C. Chenopodiaceae (Figs. 17, 4L, Q). The chenopod record probably consists partly of freshly produced pollen, a phenomenon of spring and early summer, and partly of reworked pollen, an expression of erosion. The pollen of this family characteristically has thick exine and high sporopollenin percent, making it very "robust" (durable). This durability is reflected in the large number of reworked examples from Recent, Pleistocene, and older salt marsh deposits upstream. *Salicornia* (saltwort), a salt marsh plant, clearly produces much of the chenopodiaceous pollen in these samples. (It should be noted that pollen of the Amaranthaceae is very similar to that of the Chenopodiaceae. Therefore, the two are usually united in pollen analyses as "cheno/ams." I have not done that in this study, because my fieldwork convinced me that most of the periporate pollen of this type was coming from *Salicornia*.)

FUNGAL SPORES (FIGS. 18, 3D–F, H, I)

These chitinous-walled spores are mostly produced by saprophytes, and the walls are comparable in robustness to sporopolleninous exines of pollen. Muller (1959) noted their prevalence on deltas and their scarcity offshore, implying that they do not transport well. Muller postulated that perhaps the chitinous-walled spore coats have a relatively high specific gravity (there are, however, many *non*-chitinous-walled fungal spores that are abundant aerosol particles worldwide). The lower Trinity record for 1961–1962 shows that fungal spores are abundant in the water with no obvious

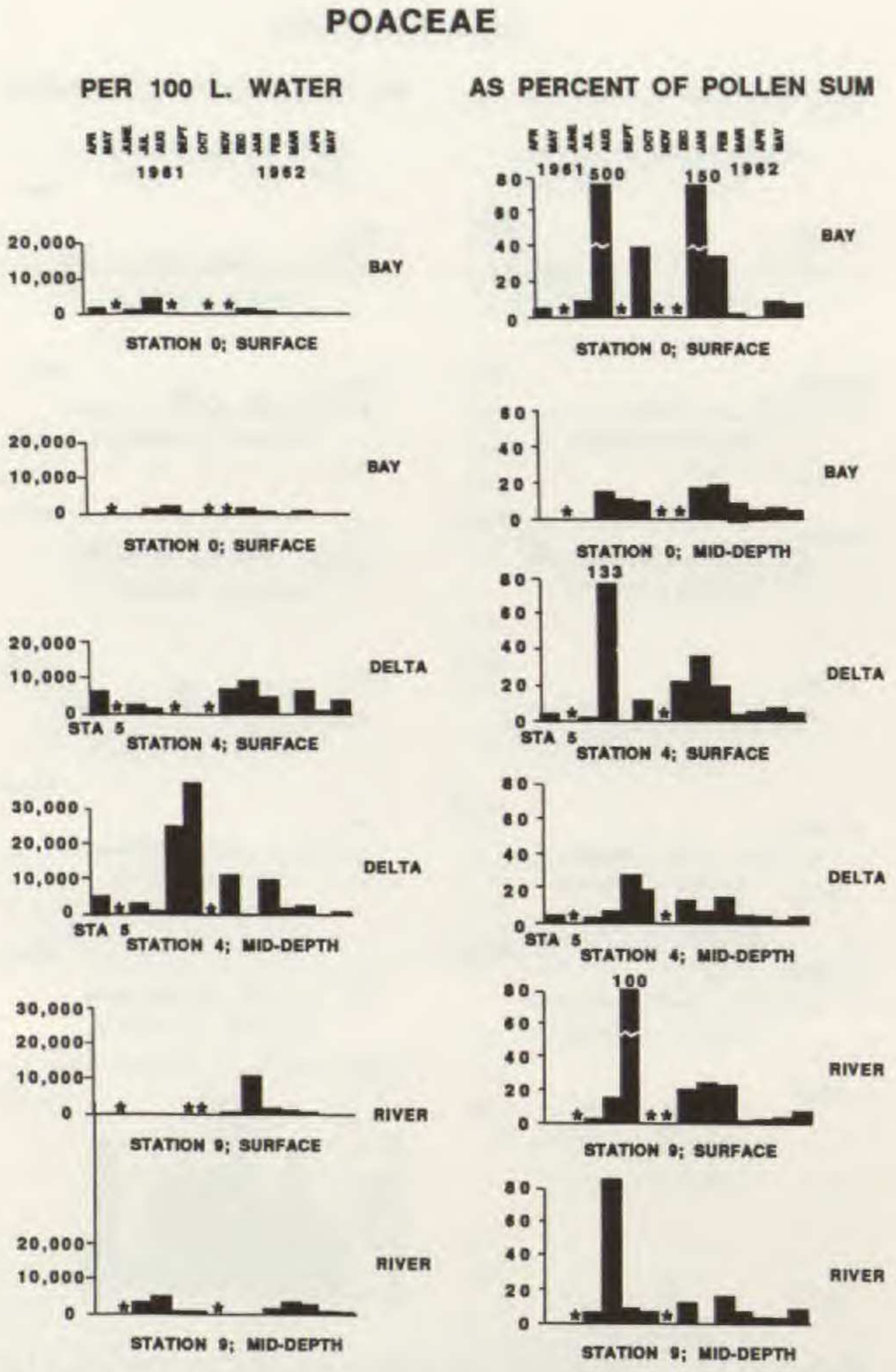

FIGURE 15. Monthly distribution of Poaceae pollen, 1961–1962, at stations 09, 04, 00, expressed per volume of water and as percentage of pollen sum. Asterisk indicates no sample.

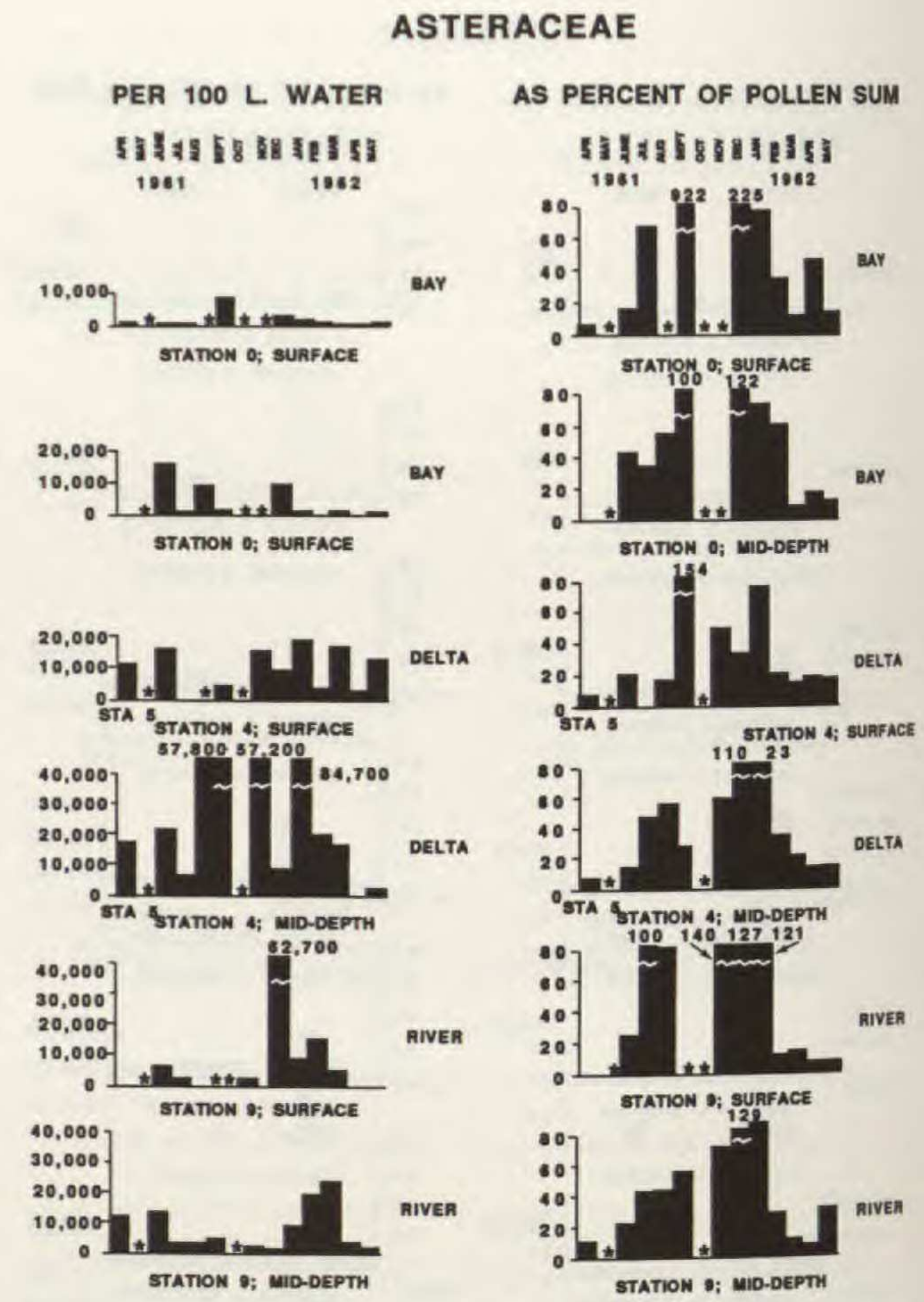

FIGURE 16. Monthly distribution of Asteraceae pollen, 1961–1962, at stations 09, 04, 00, expressed per volume of water and as percentage of pollen sum. Asterisk indicates no sample.

seasonal pattern. They are not expressed as a percentage of (tree) pollen sum, as they represent a category of fossils totally unrelated to the plant-pollen of the pollen sum. The 1985–1986 record for fungal spores shows for the most part the same sort of overall reduction in concentration per volume of water as is seen for pollen and spores, when compared to 1961–1962.

SUMMARY AND CONCLUSIONS

The concentration of palynomorphs per volume of water in Trinity River and Bay fluctuates greatly. The total amount per 100 liters of water in the river channel just off the delta (station 04) sometimes was as high as about 5 × 10^5 per 100 liters of water in 1961–1962 and sometimes as low as about 1 × 10^4 per 100 liters of water. This should be compared with the average report for four stations on the Volga River above the delta: 2.4 × 10^4 per 100 liters of water (Fedorova, 1952), and with an average concentration for the lower Mississippi River of about 4.5 × 10^5 per 100 liters of water (Chmura & Liu, 1990). Marine water on the Great Bahama Bank averaged 9.6 × 10^3 per

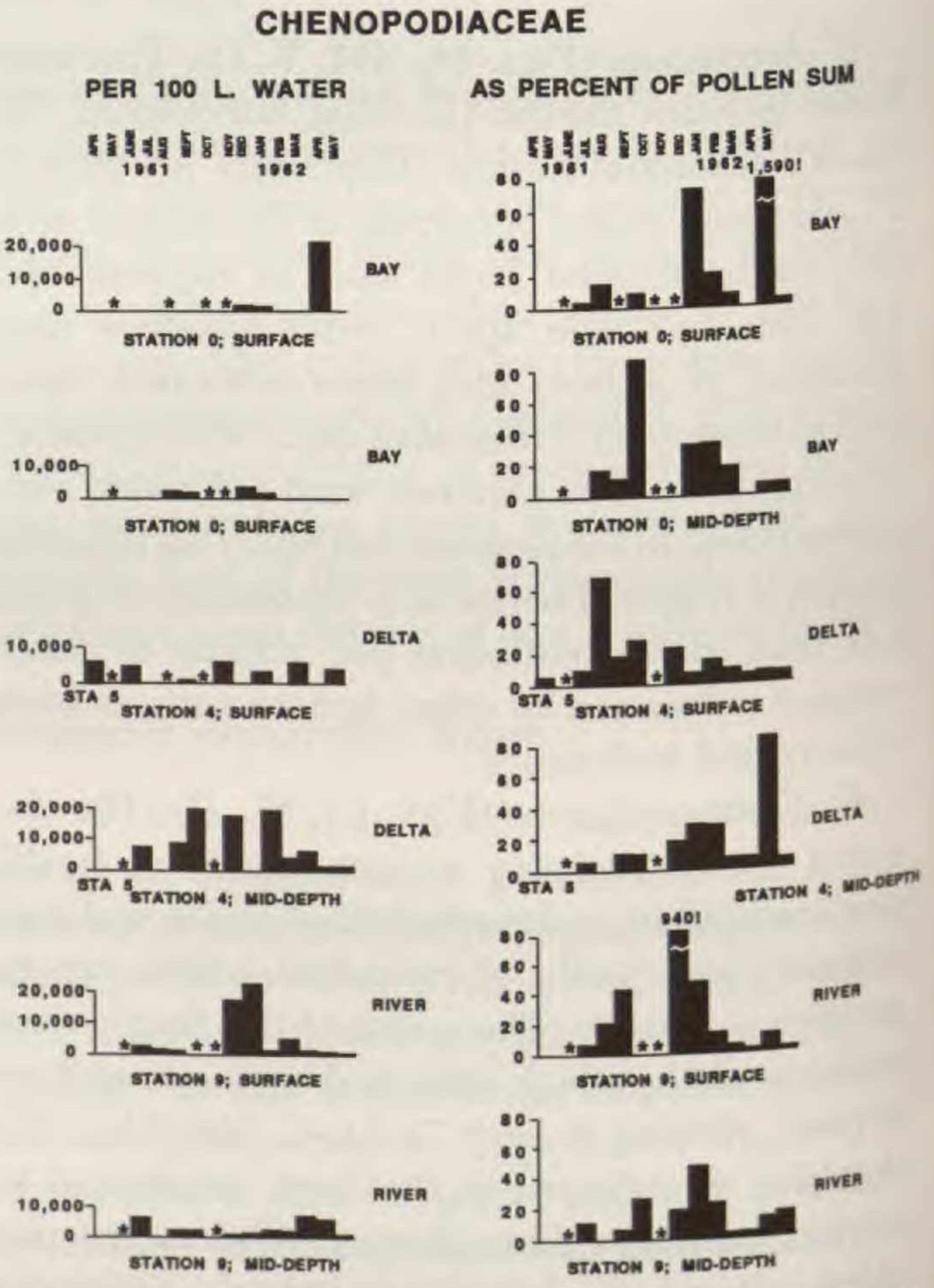

FIGURE 17. Monthly distribution of Chenopodiaceae pollen, 1961–1962, at stations 09, 04, 00, expressed per volume of water and as percentage of pollen sum. Asterisk indicates no sample.

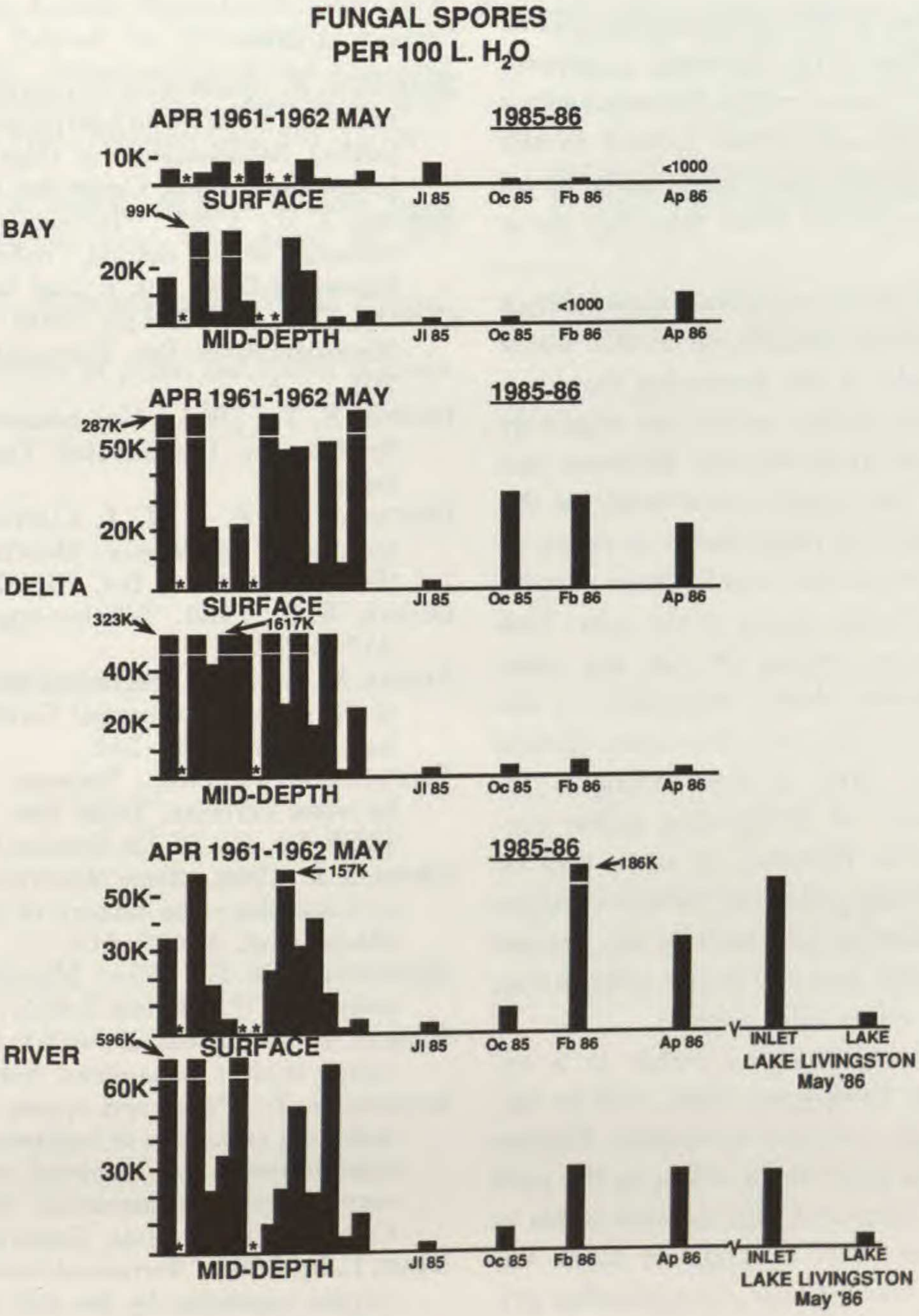

FIGURE 18. Fungal spores per 100 liters of water, 1961–1962 versus 1985–1986, for lower Trinity River and in 1985–1986 for Lake Livingston. Sampling stations as shown in Figure 1A, B.

100 liters of water (Traverse & Ginsburg, 1966). Two samples from the Gulf of Mexico near Galveston averaged 8 × 10^3 per 100 liters of water (Traverse, 1988). Presumably the higher pollen content of Gulf water reflects its high sediment content, compared with the relatively clear water of the Great Bahama Bank. As discussed in Traverse (1990), the impoundment in 1968 of Lake Livingston about 200 km north of the study area seems to have considerably reduced the palynomorph load of the water in the lower Trinity. At the same time, the proliferation of algae such as *Botryococcus* in the water of the lower Trinity since impoundment has been notable.

Water in the river channel (station 04) at the edge of the delta contains more pollen than either water from the bay (station 00) or in the river proper (station 09). As the river water discharges into the bay and loses turbulence, the pollen load settles out very quickly. As a result, the pollen content of water in the bay is usually much less than that of water from the river on the delta: in 1961–1962, station 00 (bay) averaged 1.9 × 10^4 per 100 liters of water; station 04 (delta) averaged 1.8 × 10^5 per 100 liters of water; station 09 (lower river) averaged 9 × 10^4 per 100 liters of water.

The pollen spectra of water in the river (station 09) are sometimes rather different from those of the bay (station 00), for example, in the case of Asteraceae. A complex of influences could be responsible. One possibility suggested here is that the Asteraceae pollen in the bay is mostly wind-borne, whereas that of the river is mostly a product of water action. If this is true, seasonal flowering peaks will be better represented in the bay, which seems to be the case for Asteraceae. On the other hand, for *Pinus* and *Quercus* pollen, seasonality of flowering is much more nearly reflected in the river (station 09) than in the delta (station 04) or bay (station 00). This may represent a reverse trend of that for Asteraceae, in that the tremendous quantities of pine and oak pollen formed in the immediate vicinity of the river have more of an impact on the pollen spectra there than they do in the bay.

Taxodium pollen shows a good correspondence at all locations between abundance in the water and in flowering peaks of the producing trees.

Pinus and *Quercus* pollen grains are relatively abundant in the water at all seasons. Because pine and oak pollen are the major constituents of the pollen sum, expression of these forms as ratios to the pollen sum (percentages) masks their greater absolute abundance in the spring of the year. This is especially evident at station 09. On the other hand, Asteraceae pollen shows seasonality in the percentage plots that it does not show when plotted per volume of water. Both of these examples underline the importance of interpreting pollen percentages with caution. However, it must also be emphasized that plotting pollen per volume of water has the drawback of being governed by the amount of water. For example, low pollen per volume can simply mean more water than normal.

Engelhardia/Momipites-type pollen is a reworked, presumably Paleogene, form, and its distribution is seemingly a record of erosion. Periods of abundance of this fossil in the water in the area studied may reflect previous high rainfall levels in a part of the Trinity River drainage in which Paleocene–Oligocene rocks occur. Considerable evidence of other reworked forms has been found. Foraminiferal inner tests are occasionally found in the water of Trinity River at station 09, where they are almost certainly reworked. The distribution of *Carya* pollen indicates dependence partly on the flowering peaks of the genus and partly on reworking of fossil *Carya* pollen. A similar mixed origin is suggested for Chenopodiaceae pollen, which has an extremely durable exine. Reworked chenopod pollen is probably in large part from Recent, Pleistocene, and older sediments, originally deposited under salt marsh conditions. This category may well also include some amaranthaceous pollen, as the two are virtually indistinguishable in routine analyses.

The complex of palynomorphs and palynodebris in river water near its discharge is an important reflection of: (1) events affecting the vegetation of the land which the river drains; and (2) changes in the assortment of plant biomass types sedimented, an expression of conditions and events in stream regimes.

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